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PATENT

EXCIMER OR MOLECULAR FLUORINE LASER SYSTEM WITH PRECISION TIMING

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CLAIM OF PRIORITY

This patent application claims priority to U.S. provisional patent applications " A REAL-TIME ELECTRONIC CIRCUIT FOR COMPENSATING TIME DELAY JITTER IN AN EXCIMER MOPA SYSTEM," No. 60/424,244, filed November 5, 2002; "A REAL-TIME ELECTRONIC CIRCUIT FOR COMPENSATING TIME DELAY JITTER IN AN EXCIMER MOPA SYSTEM," No. 60/427,608, filed November 18, 2002; " A REAL-TIME ELECTRONIC CIRCUIT FOR COMPENSATING TIME DELAY JITTER IN AN EXCIMER MOPA SYSTEM," No. 60/434,102, filed December 16, 2002; and " EXCIMER OR MOLECULAR FLUORINE LASER SYSTEM WITH PRECISION TIMING," No. 60/452,719, filed March 6, 2003; all of which are incorporated herein by reference.

CROSS-REFERENCE TO RELATED APPLICATIONS

The following applications are cross-referenced and hereby incorporated herein by reference:

U.S. Patent Application No. [Not Yet Assigned], entitled "MASTER OSCILLATOR – POWER AMPLIFIER EXCIMER LASER SYSTEM," to Gongxue Hua et al., filed October 30, 2003, Atty. Docket No. LMPY-18330;

U.S. Patent No. 6,226,307, entitled "MAGNETIC SWITCH CONTROLLED POWER SUPPLY ISOLATOR AND THYRISTOR COMMUTATING CIRCUIT," to Rainer Desor et al., November 2, 1999; and

U.S. Patent No. 6,005,880, entitled "PRECISION VARIABLE DELAY USING SATURABLE INDUCTORS," to Dirk Basting et al., filed March 21, 1997.

TECHNICAL FIELD OF THE INVENTION

The present invention relates to synchronization and time delays in high power excimer or molecular fluorine lasers, such as are useful for applications in microlithography and semiconductor processing.

BACKGROUND

Semiconductor manufacturers are currently using deep ultraviolet (DUV) lithography tools based on KrF-excimer laser systems, operating at wavelengths around 248 nm, as well as ArF-excimer laser systems, which operate at around 193 nm. Vacuum UV (VUV) tools are based on F_2-laser systems operating at around 157 nm. These relatively short wavelengths are advantageous for photolithography applications because the critical dimension, which represents the smallest resolvable feature size that can be produced photolithographically, is proportional to the wavelength used to produce that feature. The use of smaller wavelengths can provide for the manufacture of smaller and faster microprocessors, as well as larger capacity DRAMs, in a smaller package. In addition to having smaller wavelengths, such lasers have a relatively high photon energy (i.e., 7.9 eV) which is readily absorbed by high band gap materials such as quartz, synthetic quartz (SiO_2), Teflon (PTFE), and silicone, among others. This absorption leads to excimer and molecular fluorine lasers having even greater potential in a wide variety of materials processing applications. Excimer and molecular fluorine lasers having higher energy, stability, and efficiency are being developed as lithographic exposure tools for producing very small structures as chip manufacturing proceeds into the 0.18 micron regime and beyond. The desire for such submicron features comes with a price, however, as there is a need for improved processing equipment capable of consistently and reliably generating such features. Further, as excimer laser systems are the next generation to be used for micro-lithography applications, the demand of semiconductor manufacturers for powers of 40 W or more to support throughput requirements leads to further complexity and expense.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram showing a double chamber laser system that can be used in accordance with one embodiment of the present invention.

Figure 2 is a diagram showing a configuration for a pulser module and discharge chambers that can be used with the system of Figure 1.

Figure 3 is a circuit diagram showing a double discharge with common switch and common pulse compressor of the prior art.

Figure 4 is a circuit diagram for a gas discharge laser with a common solid state pulser circuit in accordance with one embodiment of the present invention.

Figure 5 is a plot showing a magnetization curve for compressor core material in accordance with one embodiment of the present invention.

Figure 6 is a circuit diagram for a gas discharge with solid state pulser, having an additional circuit for a separate pre-ionization in accordance with one embodiment of the present invention.

Figure 7 is a diagram showing the use of segmented electrodes and pre-ionization in a single discharge chamber in accordance with one embodiment of the present invention.

Figure 8 is a diagram showing a double chamber laser system with a common power supply and common pulser reset current utilized for precision timing in accordance with one embodiment of the present invention.

Figure 9 is a circuit diagram for providing jitter control in accordance with one embodiment of the present invention.

Figure 10 is a plot for an algorithm that can be used to calculate the control voltage V1 in accordance with one embodiment of the present invention.

Figure 11 is a diagram for a multi-channel system in accordance with one embodiment of the present invention.

Figure 12 is a plot showing the parametric dependence of the relative delay in accordance with one embodiment of the present invention.

Figure 13(a)-(e) is a schematic demonstration of timing in the control circuit in accordance with one embodiment of the present invention.

Figure 14 (a)-(d) shows the use of a Hall sensor for measuring the magnetic field of the core in accordance with one embodiment of the present invention.

Figure 15 (a)-(b) shows a diagram of a voltage integrator and a corersponding pulsediagram in accordance with one embodiment of the present invention.

Figure 16 is a diagram of a system using a common cooling system with two chambers in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION

As semiconductor manufacturers move toward the production of chips with smaller sizes, the requirements on the processing and manufacturing equipment, including the laser light sources, are ever increasing. In laser systems used for photolithography applications, for example, it would be desirable to move toward higher repetition rates, increased energy stability and dose control, increased system uptime, narrower output emission bandwidths, improved wavelength and bandwidth accuracy, and improved compatibility with stepper/scanner imaging systems. It also would be desirable to provide lithography light sources that deliver high spectral purity and extreme power, but that also deliver a low cost chip production. Requirements of semiconductor manufacturers for higher power and tighter bandwidth can place excessive and often competing demands on current single-chamber-based light sources. Many of these obstacles can be overcome by taking advantage of a dual-gas-discharge-chamber technology, referred to herein as MOPA (Master Oscillator - Power Amplifier) technology. MOPA technology is discussed further in U.S. Patent Application No. [Not Yet Assigned], entitled "MASTER OSCILLATOR – POWER AMPLIFIER EXCIMER LASER SYSTEM," Atty. Docket No. LMPY-18330, which is incorporated herein by reference above. MOPA technology can be used to separate the bandwidth and power generators of a laser system, as well as to separately control each gas discharge chamber, such that both the required bandwidth and pulse energy parameters can be optimized. Using a master oscillator (MO), for example, an extremely tight spectrum can be generated for high-numerical-aperture lenses at low pulse energy. A power amplifier (PA), for example, can be used to intensify the light, in order to deliver the power levels necessary for the high throughput desired by the chip manufacturers. The MOPA concept can be used with any appropriate laser, such as KrF, ArF, and F_2–based lasers. Further, a MOPA system can utilize separate switch/pulser systems for each discharge chamber (for the MO and the PA), but the use of separate switch/pulser systems typically leads to problems with synchronization, as controlling the timing between the parallel systems can be difficult.

Systems and methods in accordance with embodiments of the present invention can overcome deficiencies in existing laser systems by providing for the precise control of the timing of two or more discharges, such as discharges in a MOPA arrangement. In one such system, a laser system can have multiple gas discharge tubes or chambers driven by a common pulser. The pulser can include several initial compression stages, but can have separate final compression stages for each chamber. Improved timing precision for the discharges can be achieved through control of the pre-ionization timing in each of the tubes, and/or by control of the reset current in at least one of the final compression stages. In another system, pulser timing can be actively controlled in real-time using a feedback loop.

Figure 1 shows a solid state laser system **100** utilizing a common pulser **106**. The pulser can be used to supply first and second discharge voltages **102**, **104** to separate laser tubes or discharge chambers **112**. The discharge voltages are supplied using separated channels, with each channel containing a separate final compressor component **108**. Such a solid state laser system can include several compressor stages, such as on the order of five compressor stages. A number of initial compressor stages, such as 3, can be combined in the common pulser component **106**. The remaining compressor stages, namely 2 in this instance, including the final compressor stage **108**, can be maintained separately for each channel of the system. The majority of jitter between channels in the system, such as on the order or 90% of the jitter, can occur in the first several compressor stages for each channel. Using a common pulser circuit allows these first several stages to be combined into a single set of compressor stages, eliminating the jitter between channels that would otherwise result from separate stages for separate channels. It still can be necessary to separate at least the final compressor stages for each channel, if not the last few stages for each channel, in order to decouple the discharges and/or isolate the discharge chambers **112** from one another.

Figure 2 is a block diagram of an exemplary configuration **200** similar to that described with respect to Figure 1, containing a common pulser module **202**. As can be seen, the discharge chambers for the two channels, shown by laser tubes 1 and 2 (**206**, **208**), are in close proximity to the respective final compressor stages **204**, **208**. The main pulser component **202** can contain any appropriate components, such as may include a storage capacitor, a switch, a transformer, and one or more capacitor/inductor compression stages. As discussed above, it can be advantageous for jitter reduction to include at least one initial

compression stage in the common pulser component, while leaving at least one final compression stage outside the common pulser for each channel in order to decouple the laser tubes **206, 210**. The final compressor stages **204** and **208** for each gas discharge unit can each include one or more compression stages. As discussed below with respect to Figure 4, a final compressor stage can include any appropriate components, such as inductors (L2 and L3) and at least one capacitor (C3).

The discharge chambers for such a system can be in a MOPA configuration, utilizing a separated master oscillator and power amplifier. A high voltage level can be related to the trigger delay, due to a hold-off time in the pulser. The hold-off time can be determined by a magnetic assist component and magnetic pulse compression stages of the pulser. A higher operating voltage can lead to a shorter delay due to the existence of a shorter hold-off time. The delay can change by few nanoseconds per volt, and can be described by a formula such as the following:

$$\text{delay} \approx a{*}HV + t_0$$

Such variations of the high voltage on a pulse-to-pulse basis can be required in a typical lithography excimer laser in order to control the output pulse energy. Such a requirement can inevitably cause variations in the delay time.

An advantage to using a common pulser is that the correction of the delay for the actual voltage need only meet the relaxed requirement of the application for the total trigger-to-light delay, which can be on the order of 100 ns, whereas the relative timing precision between the chambers in the laser can be better than 1 ns. For example, referring to **Figure 4**, the timing between the issuance of a trigger pulse to the emission of light from the system can be on the order of 100 ns, but the variation in timing discharges in the master oscillator **426** and power amplifier **432** must be on the order of 1 ns. The relative timing of the discharges in the MO and PA can be much more critical than the timing between the issuance of a trigger pulse and the emission of light. The photodiode **422** can be used to detect the discharge of the master oscillator. A photodiode may not be appropriate for the power amplifier **432**, and the power amplifier can detect the arrival of the light pulse instead of the discharge of the amplifier. As such, an electronic detector **424** can be used to detect the discharge of the power amplifier **432**. The timing of the MO and PA can then be fed into the microprocessor, such that the microprocessor can make adjustments for variations in the

delay between the chambers, and/or the delay between the trigger pulse and the final light emission.

In a common pulser circuit such as that of **Figure 1**, the same voltage can be used and transferred to laser discharge chambers for each of two channels, such that the difference in trigger-to-pulse delays between the two discharges can be controlled with high precision. Moreover, since one or more of the compressor stages are common to both channels, the uncontrolled difference can be further reduced. Final compressor stages **108** can be used to control a delay difference, but can operate on a faster time scale than the initial stages. Other parameters can affect the delay, such as the temperature of the various elements in the pulser circuit. A change in temperature can manifest itself in a slow drift of the delay. Analysis of the trigger to light delay, delay drifts, and jitter behavior can show a variety of parameters which influence the resulting light pulse.

While stabilization of the average temperature can be straightforward, localized heating effects in critical components can still be significant. These effects can be separated into effects occurring on a pulse-to-pulse basis, and effects requiring a much slower time scale, such as on the order of seconds or even minutes. Additionally, the main delay changes can happen in the pulser, such that only a small variation of the delay remains in the laser chamber. The use of a common pulser can eliminate a majority of the delay variation, and can minimize the difference between the delays of each channel.

Some existing systems utilize a common source of energy for separate channels. For example, **Figure 3** shows an injection locked, double discharge laser **300** of the prior art. This laser utilizes a common single switch arrangement, where the switch can be a thyratron **307**, and in conjunction with the thyratron a magnetic switch control (MSC) **302** can be used to further control the pulse width. Following the MSC the electrical pulse from the MSC is input to different discharge circuits **316**, **318**, wherein a peaking capacitor **304** is discharged across electrodes **320** in a first discharge circuit **316,** and a peaking capacitor **306** is discharged across electrodes **322** in a second discharge circuit **318.** The MSC can be, for example, a saturable magnetic coil. The discharge capacitors **304**, **306** can be charged by a current pulse supplied by the storage capacitor **308**. This current first flows via the MSC, and the inductance of the MSC decreases until energy is released to the discharge capacitors

304, **306** and finally to the discharges **312**, **314** in the form of a relatively short pulse with high amplitude.

The approach shown in the system of Figure 3 suffers from reliability problems due to the relatively short lifetime of some of the componets. To a large extent the pulse electrical pulse width applied to the discharge chambers of **Figure 3** is determined by the switching speed of the thyratron **308**. A limitation of such a thyratron, however, is that a thyratron can have a very limited lifetime. The limited lifetime can significantly increase system cost and downtime, both of which are crucial for industrial applications An embodiment in accordance with the present invention overcomes this deficiency by utilizing a solid state switch, such as an IGBT, to cause the discharge of voltage stored on a capacitor. A solid state switch is very reliable, but can be too slow for excimer-type applications. In order to compensate for the longer switching time, pulse compression stages can be used. The pulse compression stages of a common pusler in such an embodiment can determine the pulse width of the electrical pulse which is applied to the final compression stages.

Figure 4 shows a schematic of a laser system **400** in accordance with one embodiment. The laser system will be described generally in terms of a MOPA system, which is a master oscillator power amplifier system, but much of the discussion in connection with system **400** would be applicable for any laser system where multiple discharge chambers are used. As shown in the embodiment of Figure 4, a common pulser **401** is utilized. The common pulser **401** receives a high voltage from a power supply **402**. Power supply **402** can be constructed from one or more power supplies connected in parallel, such as in a "master-slave" configuration, which can provide the voltage and charge for the laser pulse within the required time, such as between the consecutive pulses. Such a power supply can be obtained by Lambda EMI, where model LC203 has been tested in pulsed operation up to 6 kHz. The storage capacitor **404** of the common pulser can hold the charge until a trigger pulse is received and the IGBT (Insulated gate, bi-polar transistor) **406** switches the stored energy into a primary winding of transformer **408**. A magnetic assist inductor **420** can be used in a primary loop of the transformer to control current risetime. The signal can be transformed with suitable step-up ratio of about 20, for example, and can charge capacitor **410**. A saturable inductor **412** can hold off this voltage, preventing charging of capacitor **414** until a hold-off time is reached, whereby a compressed current pulse

charges **414**. In this manner, these components form a pulse compression stage in the common pulser **401**. Depending on the specific design requirements, additional pulse compression stages can be added to further modify the electrical pulse output by the common pulser. The electrical pulse from the common pulser **401** is input at node **403** into two final compression stages **428** and **430**. As discussed with respect to the common pulser, each of final compression stages **428** and **430** can utilize additional pulse compression stages to further modify the eletrical pulse input to the MO and/or PA. Final compression stage **428** outputs an electrical pulse to a gas discharge unit **426**. In a MOPA system the gas discharge unit **426** would be the master oscillator component. Final compression stage **430** outputs an electrical pulse to gas discharge unit **432**. In a MOPA system discharge unit **432** would correspond to a power amplifier. During the transfer of the pulse through the final compression stages, each pulse can be further compressed to show a fast risetime of about 50 ns on the respective peaking capacitors **416**, **418**.

In operation the master oscillator can generate a relatively lower power output beam as a result of electrical charge stored on the peaking capacitor **418** being discharged through the electrodes **417** of gas discharge unit **426**. This beam can then be transmitted to the gas discharge unit **432** of the power amplifier,wherein the energy of the beam output by the master oscillator can be amplified. The gas discharge unit **432** receives an electrical pulse from final compression stage **430**.

In operation it is desirable to be able to precisely control the timing of the electrical pulses being discharged in each of gas discharge units **426** and **432**. Figure 4 shows elements that can be used to control this timing. This exemplary system operates such that a trigger signal generator **419** applies a trigger signal to the processor **434** of the system. Depending on the voltage stored on storage capacitor **404**, and potentially on other factors, the processor **434** can determine a delay between receiving the trigger signal from generator **419** and toggling the IGBT switch **406**. In response to the closing of the IGBT switch, an electrical pulse is output through the compression stages of the common pulser **401** to final compression stages **428** and **430** at node **414**. The common pulser **401** can include a reset current unit **423** which can apply a reset current to inductors or magnetic switches of the common pulser, and can thereby provide some control over the timing and shape of the electrical pulse output by the common pulser **401**. The gas discharge unit **426** can further

include a photodetector **418**, which can generate a signal provided to TDC **407**, which can indicate the time at which a discharge or light pulse occurs in discharge unit **426**. It should be noted that different types of devices or circuits can be used to detect a discharge in the master oscillator, such as a pick off loop or other electrical sensor, to detect the actual discharge from peaking capacitor **418**. Such a sensor can be used to detect the discharge of the peaking capacitor and/or the emission of a light pulse from the master oscillator. The TDC **407** then can determine a time difference between the discharge in the discharge unit **426** and the input of the trigger pulse from the trigger pulse unit **419**. Gas discharge unit **432** also can include a device for sensing when an electrical pulse is discharged in the gas discharge unit **432**. As shown, the device can be a pick up loop inductor **424** capable of sensing when the electrical pulse is discharged from peaking capacitor **416**. Other electrical devices could also be used to determine when this discharge occurs, as discussed with respect to discharge unit **426**. The signal from device **422** is received by a TDC **405**, which can determine the difference in time between the trigger pulse and the discharge in gas discharge unit **432**. Based on information from TDCs **405** and **407**, the microprocessor **434** can determine a difference in time between the discharges in discharge units **426** and **432**. The microprocessor **434** then can use reset current module **425** to provide reset current to inductors of final compression stage **428** to adjust the timing of the discharge in gas discharge unit **426**. The microprocessor **434** can use reset current module **427** to provide reset current to inductors of final compression stage **430** to adjust the timing of the discharge in gas discharge unit **432**. By controlling the reset current applied to final compression stages **428** and **430**, the microprocessor **434** can precisely control a time difference in electrical pulses being applied to the gas discharge units **426** and **432**. In typical operation it can be desirable to provide a very short delay between the discharge of a master oscillator and power amplifier.

In addition to using reset current controllers **425**, **427** to control the timing of pulses reaching the discharge units **426**, **432**, an embodiment herein also provides for controlling the timing of the preionization of gases in the discharge chambers. By controlling this preionization of the gases, the precise timing of the actual discharges between the electrodes of each chamber can be further controlled. Aspects of controlling the timing of preionization will be discussed in more detail below.

In one exemplary approach, the main sources of delay jitter and drift between the two discharges are virtually eliminated by using common and/or similar circuitry where possible. The final compressors for the channels can be as identical as possible, in order to avoid delay jitter. Such an approach can also compensate for the remaining relative jitter and delay changes coming from the final compressor and chamber itself. Also, the relative delay can be adjusted as necessary to compensate for optical pulse propagation and evolution delays.

Reset Current

As discussed above with respect to Figure 4, the reset current applied to each channel can be used to provide accurate subnanosecond timing control between the voltage outputs for each channel, as driven by a common pulser. The basic approach to introducing variable timing delays betwen branches or channels of a circuit is described in U.S. Patent No. 6,005,880, entitled "PRECISION VARIABLE DELAY USING SATURABLE INDUCTORS, " incorporated herein by reference above. Using such an approach with a common pulser system as shown in **Figure 8**, a reset current component **802** for each channel can apply a separate reset current to each final compressor stage **804**, which can function as a tuning component for the main discharge pulse of each channel. The reset current applied can be determined using a computer or processing component in combination with a mechanism for monitoring the timing of the discharges. As can be seen in Figure 8, contrasted with the system of Figure 1, it is not necessary to have a separate pre-ionization control for each channel when taking such an approach to the reset current.

In a first embodiment, a reset current supplied to one or both of the final compressor stages can be used to adjust the delay of the circuit loop. Controlling the individual delay to the final compressor stage for each channel of the system can provide a control of the delay of the output pulse from each final compressor stage. **Figure 5** shows an exemplary magnetization curve **500** for the compressor core material. The reset current can be used in a solid state pulser to reset the magnetic assist and pulse compressors to a defined state of magnetization. The time integral of the voltage drop V(t) on the saturable inductor is proportional to the total flux, as given by:

$$\int V(t)dt = - S\, N\, B,$$

where B is the magnetic flux density, S is the core cross sectional area, and N is a number of turns. The saturation flux density B_{sat} can be reached faster if the core is not completely reset before the pulse to $-B_{sat}$. Reasons for variation in the magnetization between pulses can include fluctuations in the reset current, variations in the time between pulses in the burst mode, and magnetization by "reflected" pulses. For each switching cycle, the core can be driven through the magnetization curve, where the pulser current drives the magnetic material into positive saturation and the reset current drives the core back to a defined point on the magnetization curve.

The exact position to which the core is reset on the magnetization curve can be a function of the reset current. With higher magnetization, the magnet will take longer to saturate, such that the forward current will encounter a longer delay. The influence of the reset current on the pulser delay has been found to be several nanoseconds per ampere of reset current. This makes feasible a modulation of the resulting pulser hold-off delay by fine adjustment of the reset current. The reset current can be used to adjust the nominal delay difference between the two discharges. A delay difference on the order of 20 ns, for example, can be desirable to allow the oscillator to build up the optical pulse that is consequently seeded into the amplifier. For a stable laser operation in certain embodiments, the difference in the delay of the two discharges is critical and must be stable within 1 ns.

The delay in each of the laser tubes or output compressors can be measured by a Time-to-Digital converter such as model TDC-GP1 produced by acam-messelectronic of Germany. **Figure 4** shows TDCs **405** and **407** which can each recieve input related to the discharge in the gas discharge chambers. With such a chip, the delay between the start signal (trigger input) and the stop signal (light pulse) can be measured with 250 ps resolution. As can be seen in Figure 4, a photodiode **422** can be used to measure the timing of the light pulse for one channel, while a detection component or "pick-off loop" **424** can be used to determine the timing of the discharge pulse in the discharge chamber for one of the channels. For instance, a stop signal can be generated by detecting the light pulse using the photodiode **422** and converting the pulse to 5 V TTL. A start signal can be generated using a suitable pick-up coil **424** capable of converting the current pulse at the peaking capacitor **416** to a 5V TTL pulse. It can be important to measure both the start and stop signals, as there

can be some drift in the delay between signals over time, such as may be due to temperature increases.

The correction needed to stabilize the nominal trigger-to-light pulse delay can be calculated using the measured delay time of both discharges. Such corrections can be derived, for example, from a Proportional/Integral/Derivative (PID) controller included with microprocessor tasks as is known in the art. The adjustment of the overall delay can alter the trigger time of the IGBT in order to control the overall delay. The measurement of the delay of both discharges can also provide information relating to the deviation of the relative delay from the targeted delay difference between the channels. In order to control the delay between discharges, a fine adjustment of the reset current can be made in one or both final compression stages. These corrections can be derived from second PID controller of the microprocessors tasks. The output signal of the microprocessor can be used to modulate the current supply, which can deliver the reset current to the final compression stages.

Pre-Ionization Control

As mentioned above with respect to Figure 4, systems and methods in accordance with embodiments of the present invention can utilize a separate pre-ionization circuit and pre-ionization timing to control discharge timing. The use of pre-ionization to control timing can be done in addition to any modulation of the reset current as described above. For example, referring back to **Figure 1** it can be seen that there is a separate pre-ionization module **110** for the discharge chamber **112** of each channel in the laser system **100**.

As shown in **Figure 6**, each pre-ionization circuit **608**, **610** can include, for example, a high voltage power supply **612**, a small capacitor **614**, and a switch **616**. While **Figure 6** shows two such pre-ionization circuits in series with the high frequency transformer **602**, it is possible to use more than two such circuits in series, or a single such circuit, in order to obtain the appropriate voltage. The switch **616** can be a low power solid state switch, which can be much faster than a high-power IGBT, and can provide a quick burst on the corona rod **604**, described in more detail below. While the discharge timing of an excimer laser can be determined by the applied voltage, a high quality and uniform discharge can only occur when a suitable level of pre-ionization is present in the discharge chamber. Proper pre-ionization of the gas can produce a sufficient level of electrons, ions, and charged particles to

start an avalanche gas discharge in the entire volume of a discharge gap. These separate pre-ionization modules can be controlled by a computer or processor that is part of, or in communication with, the laser system. Even though the system sends a pulse to the discharge chamber, it is necessary in such a system to receive a trigger from the ionization.

The need for sufficient preionization provides for a "fine" control over the timing of the discharges. Even if the timing differences between main pulses arriving at each chamber **112** are minimized, it is possible to further fine tune the timing by ensuring that the pre-ionization pulses for each chamber arrive substantially simultaneously. Firing a pre-ionization pulse for each chamber can ensure that the discharge from each chamber will occur with a controlled delay. So, as can be seen from **Figure 1**, if the pre-ionization modules **112** fire at the appropriate time for each channel, before the arrival of the electrical or main voltage pulses **102**, **104**, then sufficient preionization should be realized in the discharge chambers **112** at the appropriate time, such that if the main voltage pulses arrive at a slightly different time before sufficient pre-ionization, the effective discharge of the each chamber will occur at the appropriate time due to the pre-ionization trigger. The pre-ionization can also be used to control the fixed delay necessary between chambers such as in a MOPA configuration. The fine control offered by such a pre-ionization circuit can be used in combination with, or in place of, a "rough" tuning adjustment made possible by controlling the reset current as described above.

In one exemplary approach, pre-ionization is achieved using a corona discharge component that provides sufficient pre-ionization prior to the arrival of the main voltage pulse. The result of this pre-ionization is a precise timing of the gas breakdown close to the point where the peaking capacitors are charged to a maximum voltage. In the exemplary circuit **400** of **Figure 4**, the timing of the corona discharge is related to the main voltage pulse. As soon as the main voltage at the peaking capacitor C0 begins rising, this same voltage appears at the corona rod. Once the voltage exceeds a few kV, the corona current can be started. The corona rod can represent a small capacity in parallel with the peaking capacitor. In this circuit **400**, the pre-ionization can occur at the same time realtive, and prior, to the peak of the main voltage pulse.

Various embodiments allow the pre-ionization to be separated from the main discharge pulse, such that the timing of the pre-ionization can be controlled separately. The

timing of the main discharge and light pulse can then be determined in part by the timing of the pre-ionization. The two light pulses can be timed to a higher accuracy than in existing systems, provided that the pre-ionization pulse timing is more precisely controlled than the timing of the main voltage pulse. An advantage of such an approach lies in the fact that requirements on the timing of the main discharge voltage pulse can be greatly reduced. An exemplary embodiment for one of the channels is shown in **Figure 6**. The switching of the pre-ionization can require a fairly low amount of power, such as on the order of tens of Watts, such that a fast pulsed source of high voltage can be used without multiple stages of compression and the associated delay uncertainty. Such a circuit can have sufficiently low inductivity and stray capacity, however, in order to not produce displacement current through the corona rod as the voltage on the main discharge electrode rises. A circuit **600** providing for separate pre-ionization can utilize a high frequency pulse transformer **602** having sufficient isolation against the 40 kV cathode potential. Since pre-ionization can consume relatively small amounts of energy, such a circuit can be based on a fast high-voltage solid state switch, which can be virtually jitter-free. An example of such switch is a stack of FET transistors. Commercial switches of this kind are manufactured by Behlke Electronics in Germany, for example. The typical rise time of the output voltage in these switches is less than 10 ns. The switches in each channel can be timed off the main trigger pulse. Alternatively, the trigger for one (slave) channel can be referenced to the pulse of the photodetector output produced by UV emission of another (master) chamber.

A secondary winding of the high frequency transformer **602**, as shown in **Figure 6**, can be connected to a capacitor **606** and the corona rod **604** in parallel. The capacitor can override the intrinsic capacitance of the corona rod and stray capacitances of the transformer and lead wires. This can prevent stray displacement current that might otherwise occur when the voltage on the cathode rises, leading to a premature corona discharge. The two primary windings of the high frequency transformer can serve to increase the peak current delivered to the corona rod. Depending on the concrete parameters of the circuit, one or more windings can be sufficient. Separate pre-ionization can be advantageously used in combination with individual or common solid state pulsers in order to create a precisely timed double discharge system, where a separate pre-ionization source is added to each channel as in **Figure 4**.

Split electrodes to effectively lengthen pulse

In many applications using a double chamber excimer or molecular fluorine laser, a long pulse length is desired in order to minimize the peak power, thereby reducing the compaction of fused silica. Fused silica is currently the main material used in the lens of 193nm microlithography scanner, and short, intense bursts can damage such a lens. It is not a matter of simply creating a longer pulse in an excimer laser system, as longer pulses tend to become unstable. Systems and methods in accordance with embodiments of the present invention can utilize an optical pulse extender to "stretch" the laser pulse. The pulse can also be extended by increasing the discharge duration in the amplifier of a MOPA system by splitting the discharge electrodes and controlling the delay between segments of the split electrodes. Multiple sets of electrodes, such as for example two pair of electrodes, or portions of the same electrode pair, can be aligned to the same optical axis. **Figure 7** shows such a configuration **700**, with segmented electrodes **704**, **706** and pre-ionization components **708**, **710** in a single discharge chamber **702**. The main discharge along these electrode segments can be performed with a selected delay and, as a result, the inversion time of the amplifier can be extended. With an appropriately long seed pulse from the oscillator, the output can be extracted over the entire period of time. In a practical arrangement, the timing difference between the two main discharges can be on the order of about 10 – 30 ns. A separate final compressor circuit, pre-ionization circuit, or sub-channel can be used for each electrode segment in order to generate the appropriate delays between segments. Firing the electrodes at slightly different times, using a controlled delay, can result in a longer gain pulse that has the same energy, but lower peak intensity, than a pulse created using non-segmented electrodes.

The first discharge can occur after an appropriate discharge voltage is reached and pre-ionization has occurred, in order to produce the required start-up electron and ion density for the avalanche gas discharge. The pre-ionization pulse can be applied to the second discharge with the desired delay, such as about 20 ns, which can lead to a delayed gas discharge in that section of the laser tube. The final result can be a total discharge time that is extended by approximately 20 ns. Favorable gas and voltage conditions can be maintained, such that the peaking voltage remains stable and can discharge after pre-

ionization. The timing jitter of the pre-ionization pulse to the main discharge can be on the order of less than 1 ns.

Circuits described herein can be used to switch the pre-ionization of one or both of the segments with controlled delay. A low energy 193nm light pulse can be utilized in one embodiment to produce near-perfect pre-ionization of a large cross section 193nm discharge area. In a linear arrangement of the segmented electrodes, the UV-light pulse of the first segment can be utilized for the pre-ionization of the gas in the second segment. In such an arrangement, an automated timing of the second segment can be achieved.

Real-Time Compensation

Systems and methods in accordance with embodiments of the present invention can also utilize a circuit allowing for real-time compensation of the time delay jitter of a discharge pulse in an excimer laser with magnetic pulse compression. Such an adjustment can be fast enough to be based on the actual parameter affecting the delay, such as the charging voltage of storage capacitor, as opposed to a slower algorithm based on delays experienced in prior pulses. The timing variation between trigger pulses can be predicted by monitoring at least one parameter of the discharge, then predicting the variation in the next pulse. Such an approach can also be used to compensate for jitter between channels when using a common pulser.

Such a circuit can add fast, real-time capability for adjusting the timing of the discharge in an excimer laser. Such timing can be important in MOPA systems, where time jitter typically has to be controlled to sub-nanosecond levels. The jitter can have multiple causes, which can be divided into "slow" and "fast" mechanisms. Slow jitter mechanisms have characteristic times that are longer than the time interval between pulses. An example of a slow mechanism is the drift due to temperature variations in the laser discharge unit. Fast jitter mechanisms can alter the delay on a time scale that is shorter than the pulse period. Examples of a fast mechanism include fluctuations of the charging voltage of the primary storage capacitor. Slow drifts can be compensated for by a feedback loop that measures the actual time delay between oscillator and amplifier discharge pulses, and which adjusts a relative delay for the next pulse. For example, a closed PID circuit can be used to measure the timing of pulses, compare the timing to at least one set point, and generate an error signal

based on the difference between the timing and the set point. A computer or processor can then generate a correction for the delay line based on the error signal. While such an approach can be acceptable for slow drifts, it should be understood that such a process can be slow and can require a number of pulse measurements, such that it is not appropriate for all drifts.

For fast drifts, the parameter causing the drift, such as the voltage on the capacitor, can be measured in real time and adjusted before the pulse is triggered. The adjustment can be made using a known dependence of delay on the parameter. A fast, open loop system can be used to monitor parameters such as the high voltage, reset current, and core magnetizations of a pulse-to-pulse basis. A computer or processor can then recalculate a correction, or generate a correction, for each pulse generated. Such an approach can also be used with a common pulser system, as second order effects will exist even though a common high voltage is being used. Further, different corrections might be needed for the final compressor stage of each channel.

Therefore, while slow drifts can be compensated for by a digital circuit or microprocessor, a fast analog circuit can be added to compensate for the fast jitter of each individual pulse. While the embodiments described herein are generally drawn to jitter control techniques for MOPA systems, and particularly excimer or molecular fluorine laser systems, the principles of these techniques can also be applied to other systems as well, such as dual- or multi-discharge chamber laser systems and solid state laser MOPA systems, systems utilizing separate channels, or systems utilizing a common pulser component.

Figure 9 shows one such circuit **900** in accordance with embodiments of the present invention. In the circuit, a high voltage supply module **902** charges the storage capacitor **904**. A fast switch **906** initiates discharging of the capacitor **904** into a pulse compression circuit loaded onto the discharge chamber. The optical pulses in the oscillator and amplifier chambers are detected by photodiodes **908** and **910**, respectively. Information about the relative delay between optical pulses is input to a processing unit **912**, which can include a microprocessor to perform a slow adjustment algorithm. In existing systems, the output of such a unit is used to trigger the switch. In this embodiment, however, a fast-acting analog circuit is added such that a delay generated by this circuit can be added to the overall delay generated by the slow digital feedback loop. The analog circuit can consist generally of

several channels, one for each parameter affecting jitter. One channel can compensate for jitter caused by charging voltage instabilities, while another channel can be used to compensate for variations in reset current. The output of each channel can be a voltage that is proportional to the required delay, e.g., V1 to V4. The voltages from all such channels can be summed and input to a comparator **914**. The other input of the comparator can be generated by a saw voltage generator **916**, which can be synchronized to the trigger pulse from the slow control unit. As a result, the comparator **914** can output a pulse having a delay with respect to the trigger pulse that is proportional to the sum of the voltages V1…V4.

Figure 10 shows a plot **1000** for an algorithm that can be used to calculate a control voltage V_l based on the input voltage V_d from the high voltage divider. The output pulse delay of the magnetic pulse compressor varies depending on the charging voltage with a coefficient of roughly 2 ns/V. The exact dependence is generally non-linear, can be measured experimentally, and can be programmed into an analog circuit that can perform polynomial approximation of this function. Such an analog circuit can be built from several operational amplifiers, or can be based on a programmable analog (PAC) IC. An example of a commercially available PAC is the ispPAC-series of programmable analog ICs from Lattice Semiconductor Corporation of Hillsboro, OR. The time response of such an analog circuit can be dependent on the frequency bandwidth of the IC. Such devices typically have a bandwidth of at least 1 MHz, which converts into the response time of better than 1 micro-second.

Various configurations of such a circuit are also possible. For example, the slow control unit can be used to output voltage instead of a trigger pulse. This voltage can be summed with voltages V1 to V4, such that the voltage adds to the total delay. Further, the saw voltage generator can be triggered by a master trigger pulse from a user machine or internal clock. Such a choice can be based on convenience, since generating voltage in a digital system is typically less accurate than generating a delayed pulse.

Figure 11 shows an embodiment of a real-time compensating circuit **1100** that can be used with a two-channel MOPA system. Each channel can have a high voltage power supply **1102, 1104**, a storage capacitor **1106, 1108**, and a solid state switch **1110, 1112**, followed by the pulse compression circuits of the pulser. The voltages on the storage capacitors are Vs1 and Vs2 for channels 1 and 2, respectively. Since it is the difference in

charging voltages that has an effect on the relative delay, it can be more practical to directly measure the difference between Vs1 and Vs2 using a differential high voltage probe **1114**, whereby higher resolution can be achieved. The voltage difference can be input to the programmable analog device **1116** with the probe attenuation coefficient α. The programmable analog device can perform an analog computation of the output voltage that is proportional to the required compensating delay between channels 1 and 2. The algorithm can be based on pre-measured dependencies of the delay in each pulser **1118, 1120**. Such dependence can be a generally non-linear function, but can be approximated using a linear dependence in the small range where slope changes, depending on the absolute value of the voltage. As the slope can be different in each channel, the dependence of voltage V1 that is necessary to compensate for a relative delay between channels, on the voltage differential between channels, can parametrically depend on the voltage in either channel. This is schematically illustrated in the plot **1200** of **Figure 12**, where each branch of parametric dependence is shown as approximately linear, with the slope dependent in this example on the high voltage in channel 2.

The voltage V1 output from the programmable analog device is proportional to the relative delay between the channels that is necessary to compensate for relative jitter caused by the charging voltage fluctuations between pulses. Since the response time of such a device is very short, such as on the order of microsecond or shorter, the algorithm can compensate jitter for each individual pulse.

Figure 11 also shows that there can be more inputs in the "fast" branch of the control circuit, shown as V2, V3, V4, and so on. These inputs can be based on other parameters, such as an initial magnetization of cores, that vary from pulse to pulse, and that also have a well characterized effect on the overall delay in the pulser. These control voltages can be generated in a similar fashion using a programmable analog device that takes its input voltage from an appropriate sensor.

Instead of using a fast analog algorithm, a slower algorithm, such as a slow digital algorithm, can be used to compensate for slower drifts, such as may be caused by temperature variations. These drifts can occur over many pulses, such that a slow algorithm can utilize the average input and make relatively small adjustments of the delay for each pulse. For such an algorithm, the input can be generated by photodiodes **1122**, **1124** for each

channel using the actual delay between optical pulses in each channel. This delay information can be averaged over several pulses, and used to increase or decrease the compensating trigger delay between channels. Averaging can effectively decouple a fast algorithm from a slow algorithm, as fast changes average out in a slow algorithm and slow changes are too small, on a per pulse basis, to be felt in the fast algorithm.

Figure 11 also shows that there can be additional inputs to the slow digital control unit **1126**. These inputs can be generally based on any other slow varying parameters that can be measured in absolute terms. For example, one may want to vary the relative timing of the amplified pulse with respect to the amplifier gain pulse, depending on the age of the laser gas. In this case, the number of pulses elapsed since the gas replacement can serve as an input to the slow algorithm.

Figure 13(a)-(e) shows exemlary plots **1300** that schematically illustrate timing in the control circuit. The process can be initiated by a master trigger at t_o. The digital control unit can generate a delayed trigger pulse t_1 for one of the channels, such as channel 1 in the example of **Figure 13(a)**. This delay can be necessary in certain embodiments for performing a number of functions in the laser. While some users may require that the master trigger begin charging the storage capacitors, some users may allow the master trigger to occur after the capacitors have been charged. In any case, the delay can be a fixed delay common to both channels. The trigger pulse for the second channel at t_2 is delayed with respect to t_1 by an amount calculated by the slow algorithm as seen in **Figure 13(b)**. The relative delay (t_2-t_1) can be either positive or negative. The trigger pulse t_2 can start another generator of fixed delay t_2 (see Figures 11 and 13(d)), which may be necessary to compensate for the average value of the fast varying component of the delay in channel 1. Delay generator t_2 is shown here as a separate unit only for illustrative purposes, but can be built into the time t_2 already in the digital control unit. The trigger pulse t_1, on the other hand, can start the saw-voltage generator in order to add fast varying delay t_1, as shown in **Figure 13(c)**. Both delays t_1 and t_2 are on the order of 10 to 100 nsec. Trigger pulses t_1+ t_1 and t_2+ t_2 shown in **Figures 13(c)** and **13(d)**, respectively, have a relative delay that can be necessary to compensate for the total relative delay in two channels. Finally, a laser pulse can be emitted as shown in **Figure 13(e)**, with the delay that naturally occurs due to the electrical pulse compression in the pulser and the optical pulse evolution in the resonator.

Figure 14 shows an example of a sensor for the initial magnetization state of the cores before receiving the pulse. Since there is always some energy in a solid state pulser that is reflected back from the discharge, magnetization can vary between pulses. Varying magnetization can be especially harmful for a burst mode where timing varies between pulses. The total effect of magnetization by reflected current pulses and constant reset current can then vary as well.

Figure 14 shows a configuration utilizing a Hall sensor for measuring a magnetic field of the core just prior to a discharge pulse. The value of the magnetic field can be converted into voltage and input to the fast feedback loop. **Figure 14(a)** shows a schematic diagram **1400** of a portion of a magnetic compressor based on a Melville line, having a Hall sensor, or magnetic field sensor, disposed therein. **Figure 14(b)** shows a side view of a Hall sensor configuration **1410**, detailing the placement of the sensor **1412** on the core **1414**. Since the core has a thoroidal shape, the magnetic field can be contained almost completely inside the core material. The sensor **1412** can be placed advantageously into a small recess **1416** on the surface of the core, in order to allow a small amount of field to leak. **Figure 14(c)** is a perspective view of the sensor, showing schematically the direction of magnetic induction vector B and electric current I. The potential difference can be measured between the front and back surfaces of the chip, as seen in the Figure. This potential difference can be proportional to the strength of the magnetic field. An example of a commercially available Hall sensor is Model 3503, a ratiometric linear Hall-effect sensor manufactured by Allegro Microsystems, Inc. of Worcester, MA. The sensor has a response value of 1.3 mV/Gauss, so the response is 10.4 V at the maximum saturation flux density of a typical core material of 0.8 Tesla. **Figure 14(d)** shows a magnetization loop **1430** of the core, as well as the trajectory in B(H) space during the laser operation. In a perfectly "reset" core, the trajectory starts at point t_1. Due to the leakage current, the trajectory progresses to a threshold of saturation at t_2, The main pulse is then generated, reaching a maximum value of electric current at t_3. Following the main pulse, the reset current returns the core to the initial state t_1, altough in a real-world system some parameter variation can cause the trajectory to return to state t_4, instead of intial state t_1. With the core in state t_4, the magnetization that results in the flux density can be lower than saturated flux density B_{sat}. Therefore, when the next pulse arrives, the trajectory can proceed through the state t_5 with reduced flux content.

This can result in a reduced "hold-off" time for the next compressed pulse. The sensor can detect the value of magnetic flux density B in the initial state, which is dependent on the magnetization, and can provide information to the regulation loop regarding the flux content of the core.

Figure 15 shows schematically another circuit **1500** based on a voltage integrator, which can be used in accordance with another embodiment of the present invention. A saturable inductor **1502** can be used, which has an additional, relatively small winding **1504**. The voltage generated in this additional winding can follow the waveform of the voltage drop on the main winding, and the voltage, Vs, can be proportional to the voltage drop on the main winding. The time integral of this voltage can serve as a measure of change in magnetization state of the core, as discussed herein. Integration can be done by means of capacitor Cs **1506**, where the time constant R_sC_s is greater than the time between pulses. The integrator can be reset before each pulse by switch K_s **1508**. At the end of the integration cycle, the voltage output of capacitor Cs **1506** is a measure of magnetization increment that occurred between the pulses. **Figure 15(b)** shows a plot **1510** illustrating that the integration occurs over the main pulse, as well as over possible reflected pulses expected to arrive within several microseconds after the main pulse. The reset current also can contribute to this value. The generated voltage can be sampled at the end of the integration cycle, and can serve as an additional input to the fast regulation loop.

Common Cooling

Figure 16 shows a diagram of a laser system **1600** that can be used in accordance with another embodiment. This system utilizes first and second pulsers **1608, 1610** to drive first and second chambers **1604, 1606** using a common cooling system **1602**, such as a common oil bath, for equalizing the temperatures of the channels corresponding to the chambers. The chambers **1604, 1606** can be tilted relative to the common cooler arrangement, in order to reduce the spacing between the sets of electrodes **1614** for the chambers **1604, 1606**. The spacing reduction can help to minimize the inductance of lead components. In a variation of this configuration, a common pulser can be used, which in one embodiment can have two separate final compressor stages.

It should be recognized that a number of variations of the above-identified embodiments will be obvious to one of ordinary skill in the art in view of the foregoing description. Accordingly, the invention is not to be limited by those specific embodiments and methods of the present invention shown and described herein. Rather, the scope of the invention is to be defined by the following claims and their equivalents.